

Suppression of flavor violation in an A_4 warped extra dimensional model

Avihay Kadosh

Center for Theoretical Physics, University of Groningen
9747AG, Groningen, The Netherlands

E-mail: a.kadosh@rug.nl

Abstract. In an attempt to simultaneously explain the observed masses and mixing patterns of both quarks and leptons, we recently proposed a model (JHEP08(2010)115) based on the non abelian discrete flavor group A_4 , implemented in a custodial RS setup with a bulk Higgs. We showed that the standard model flavor structure can be realized within the zero mode approximation (ZMA), with nearly TBM neutrino mixing and a realistic CKM matrix with rather mild assumptions. An important advantage of this framework with respect to flavor anarchic models is the vanishing of the dangerous tree level KK gluon contribution to ϵ_K and the suppression of the new physics one loop contributions to the neutron EDM, ϵ'/ϵ , $b \rightarrow s\gamma$ and Higgs mediated flavor changing neutral current (FCNC) processes. These results are obtained beyond the ZMA, in order to account for the full flavor structure and mixing of the zero modes and first Kaluza-Klein (KK) modes of all generations. The resulting constraints on the KK mass scale are shown to be significantly relaxed compared to the flavour anarchic case, showing explicitly the role of non abelian discrete flavor symmetries in relaxing flavor violation bounds within the RS setup. As a byproduct of our analysis we also obtain the same contributions for the custodial anarchic case with two $SU(2)_R$ doublets for each fermion generation.

1. Introduction

Recently we have proposed a model [1] based on a bulk A_4 flavor symmetry [2] in warped geometry [3], in an attempt to account for the hierarchical charged fermion masses, the hierarchical mixing pattern in the quark sector and the large mixing angles and the mild hierarchy of masses in the neutrino sector. In analogy with a previous RS realization of A_4 for the lepton sector [4], the three generations of left-handed quark doublets are unified into a triplet of A_4 ; this assignment forbids tree level FCNCs driven by the exchange of KK gauge bosons. The scalar sector of the RS- A_4 model consists of two bulk flavon fields, in addition to a bulk Higgs field. The bulk flavons transform as triplets of A_4 , and allow for a complete "cross-talk" [5] between the $A_4 \rightarrow Z_2$ spontaneous symmetry breaking (SSB) pattern associated with the heavy neutrino sector - with scalar mediator peaked towards the UV brane - and the $A_4 \rightarrow Z_3$ SSB pattern associated with the quark and charged lepton sectors - with scalar mediator peaked towards the IR brane - and allows to obtain realistic masses and almost realistic mixing angles in the quark sector. A bulk custodial symmetry, broken differently at the two branes [6], guarantees the suppression of large contributions to electroweak precision observables [7], such as the Peskin-Takeuchi S , T parameters. However, the mixing between zero modes of

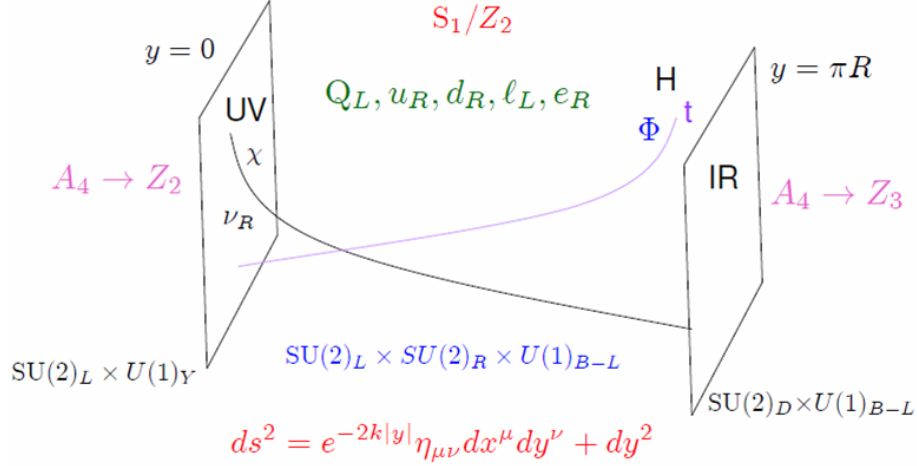


Figure 1. A pictorial description of the RS- A_4 setup. The bulk geometry is described by the metric at the bottom and $k \simeq M_{Pl}$ is the AdS_5 curvature scale. All fields propagate in the bulk and the UV(IR) peaked nature of the heavy RH neutrinos, the Higgs field, the t quark and the A_4 flavons, Φ and χ , is emphasized. The SSB patterns of the bulk symmetries on the UV and IR branes are specified on the side (for A_4) and on the bottom (for $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$) of each brane.

the 5D theory and their Kaluza-Klein (KK) excitations – after 4D reduction – may still cause significant new physics (NP) contributions to SM suppressed flavor changing neutral current (FCNC) processes.

In general, when no additional flavor symmetries are present and the 5D Yukawa matrices are anarchical, FCNC processes are already generated at the tree level by a KK gauge boson exchange [8]. Stringent constraints on the KK scale come from the $K^0 - \bar{K}^0$ oscillation parameter ϵ_K , the radiative decays $b \rightarrow s(d)\gamma$ [8, 9], the direct CP violation parameter ϵ'/ϵ_K [10], and especially the neutron electric dipole moment (EDM) [8], also in the presence of an RS-GIM suppression mechanism [11, 12].

Conclusions may differ if a flavor pattern of the Yukawa couplings is assumed to hold in the 5D theory due to bulk flavor symmetries. They typically imply an increased alignment between the 4D fermion mass matrix and the Yukawa and gauge couplings, thus suppressing the amount of flavor violation induced by the interactions with KK states.

In our case, the most relevant consequence of imposing an A_4 flavor symmetry is the degeneracy of the left-handed fermion bulk profiles f_Q , i.e. $diag(f_{Q_1, Q_2, Q_3}) = f_Q \times \mathbb{1}$. In addition, the distribution of phases, CKM and Majorana-like, in the mixing matrices might induce zeros in the imaginary components of the Wilson coefficients contributing to CP violating quantities.

In the following we review the most relevant features of the RS- A_4 model [1] and its phenomenological consequences [13]. In particular, we discuss helicity flipping FCNC processes induced by dipole operators and obtain the most significant constraints coming from $b \rightarrow s\gamma$, $\text{Re}(\epsilon'/\epsilon_K)$ and the neutron EDM. As a byproduct we obtain the analogous constraints in a custodial anarchic scheme with a bulk Higgs. Implications of adopting a P_{LR} extended custodial setup [17] are then briefly discussed.

2. The RS- A_4 model

The RS- A_4 setup [1] is illustrated in Fig. 1. The bulk geometry is that of a slice of AdS_5 compactified on an orbifold S_1/Z_2 [3] and is described by the metric on the bottom of Fig. 1.

All 5D fermionic fields propagate in the bulk and transform under the following representations of $(SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}) \times A_4[1]$:

$$\begin{aligned}
Q_L &\sim (3, 2, 1, \frac{1}{3}) (\underline{\mathbf{3}}) & \ell_L &\sim (1, 2, 1, -1) (\underline{\mathbf{3}}) \\
u_R \oplus u'_R \oplus u''_R &\sim (3, 1, 2, \frac{1}{3}) (\underline{\mathbf{1}} \oplus \underline{\mathbf{1}}' \oplus \underline{\mathbf{1}}'') & \nu_R &\sim (1, 1, 2, 0) (\underline{\mathbf{3}}) \\
d_R \oplus d'_R \oplus d''_R &\sim (3, 1, 2, \frac{1}{3}) (\underline{\mathbf{1}} \oplus \underline{\mathbf{1}}' \oplus \underline{\mathbf{1}}'') & e_R \oplus e'_R \oplus e''_R &\sim (1, 1, 2, -1) (\underline{\mathbf{1}} \oplus \underline{\mathbf{1}}' \oplus \underline{\mathbf{1}}'') .
\end{aligned} \tag{1}$$

The SM fermions (including RH neutrinos) are identified with the zero modes of the 5D fermions above. The zero (and KK) mode profiles are determined by the bulk mass of the corresponding 5D fermion, denoted by $c_{qL, u_i, d_i} k$ (and BC)[13]. The scalar sector contains the IR peaked Higgs field and the UV and IR peaked flavons, χ and Φ , respectively. They transform as:

$$\Phi \sim (1, 1, 1, 0) (\underline{\mathbf{3}}), \quad \chi \sim (1, 1, 1, 0) (\underline{\mathbf{3}}), \quad H \sim (1, 2, 2, 0) (\underline{\mathbf{1}}). \tag{2}$$

The SM Higgs field is identified with the first KK mode of H . All fermionic zero modes acquire masses through Yukawa interactions with the Higgs field and the A_4 flavons after SSB. The 5D $(SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}) \times A_4$ invariant Yukawa Lagrangian will consist of leading order(LO) UV/IR peaked interactions and next to leading order (NLO) "cross-talk" and "cross-brane" interactions[1]. The LO interactions in the neutrino sector are shown in [1] using the see-saw I mechanism, to induce a tribimaximal (TBM)[14] pattern for neutrino mixing while NLO "cross brane" and "cross talk" interactions, induce small deviations of $\mathcal{O}(0.04)$, which are still in good agreement with the current experimental bounds [15]. Here, we focus on the quark sector and on the phenomenology relevant for flavor and CP violating processes. The relevant terms of the 5D Yukawa lagrangian are of the following form:

$$\mathcal{L}_{5D}^{Yuk.} = \mathcal{L}_{LO} + \mathcal{L}_{NLO} = \frac{1}{k^2} \overline{Q}_L \Phi H(u_R^{(l, ')}), d_R^{(l, ')} + \frac{1}{k^{3/2}} \overline{Q}_L \Phi \chi H(u_R^{(l, ')}), d_R^{(l, ')} \tag{3}$$

Notice that the LO interactions are peaked towards the IR brane while the NLO interactions mediate between the two branes due to the presence of both Φ and χ .

The VEV and physical profiles for the bulk scalars are obtained by solving the corresponding equations of motion with a UV/IR localized quartic potential term and an IR/UV localized mass term [18]. In this way one can obtain either UV or IR peaked and also flat profiles depending on the bulk mass and the choice of boundary conditions. The resulting VEV profiles of the RS- A_4 scalar sector are:

$$v_{H(\Phi)}^{5D} = H_0(\phi_0) e^{(2+\beta_{H(\Phi)})k(|y|-\pi R)} \quad v_{\chi}^{5D} = \chi_0 e^{(2-\beta_{\chi})k|y|} (1 - e^{(2\beta_{\chi})k(|y|-\pi R)}), \tag{4}$$

where $\beta_{H\Phi, \chi} = \sqrt{4 + \mu_{H, \Phi, \chi}^2}$, and $\mu_{H, \Phi, \chi}$ is the bulk mass of the corresponding scalar in units of k , the cutoff of the 5D theory. The following vacua for the Higgs and the A_4 flavons Φ and χ

$$\langle \Phi \rangle = (v_{\phi}, v_{\phi}, v_{\phi}) \quad \langle \chi \rangle = (0, v_{\chi}, 0) \quad \langle H \rangle = v_H \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \tag{5}$$

provide at LO TBM neutrino mixing and zero quark mixing [2, 5]. The stability of the above vacuum alignment is discussed in [1]. The VEV of Φ induces an $A_4 \rightarrow Z_3$ SSB pattern, which in turn induces no quark mixing and is peaked towards the IR brane. Similarly, the VEV of χ induces an $A_4 \rightarrow Z_2$ SSB pattern peaked towards the UV brane and is in charge of the TBM mixing pattern in the neutrino sector. Subsequently, NLO interactions break A_4 completely and induce quark mixing and deviations from TBM, both in good agreement with experimental

data. The Higgs VEV is in charge of the SSB pattern $SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$, which is peaked towards the IR brane. The (gauge) SSB pattern on the UV brane is driven by orbifold BC and a planckian UV localized VEV, which is effectively decoupled from the model.

To summarize the implications of the NLO interactions in the quark sector, we provide the structure of the LO+NLO quark mass matrices in the ZMA [1]:

$$\frac{1}{v}(M + \Delta M)_{u,d} = \underbrace{\begin{pmatrix} y_{u,d}^{4D} & y_{c,s}^{4D} & y_{t,b}^{4D} \\ y_{u,d}^{4D} & \omega y_{c,s}^{4D} & \omega^2 y_{t,b}^{4D} \\ y_{u,d}^{4D} & \omega^2 y_{c,s}^{4D} & \omega y_{t,b}^{4D} \end{pmatrix}}_{\sqrt{3}U(\omega)\text{diag}(y_{u_i,d_i}^{4D})} + \begin{pmatrix} f_\chi^{u,d} \tilde{x}_1^{u,d} & f_\chi^{c,s} \tilde{x}_2^{u,d} & f_\chi^{t,b} \tilde{x}_3^{u,d} \\ 0 & 0 & 0 \\ f_\chi^{u,d} \tilde{y}_1^{u,d} & f_\chi^{c,s} \tilde{y}_2^{u,d} & f_\chi^{t,b} \tilde{y}_3^{u,d} \end{pmatrix} \quad (6)$$

where $\omega = e^{2\pi i/3}$, $v = 174\text{GeV}$ is the 4D Higgs VEV, $y_{u,c,t,d,s,b}^{4D}$ are the effective 4D LO Yukawa couplings and $\tilde{x}_i^{u,d}$, $\tilde{y}_i^{u,d}$ are the coefficients of the 5D NLO Yukawa interactions. The function $f_\chi^{u_i,d_i} \simeq 2\beta_\chi C_\chi / (12 - c_{qL} - c_{u_i,d_i}) \simeq 0.05$ is the characteristic suppression of the 4D effective NLO Yukawa interactions and $C_\chi = \chi_0/M_{Pl}^{3/2} \simeq 0.155$. Finally, the unitary matrix, $U(\omega)$ is the LO left diagonalization matrix in both the up and down sectors, $(V_L^{u,d})_{LO}$, which is independent of the LO Yukawa couplings, while $(V_R^{u,d})_{LO} = \mathbb{1}$ (see [1]). Using standard perturbative techniques on the matrix in Eq. (6) we obtained $(V_{L,R}^{u,d})_{NLO}$ [1, 13] at $\mathcal{O}(f_\chi^{u_i,d_i}(\tilde{x}_i^{u,d}, \tilde{y}_i^{u,d}))$ and showed that by a rather mild deviation from a universality assumption on the magnitudes and phases of the NLO coefficients, $\tilde{x}_i^{u,d}, \tilde{y}_i^{u,d}$, we are able to obtain an almost realistic CKM matrix of the characteristic form [1]:

$$V_{CKM} = \begin{pmatrix} 1 & a\lambda & b\lambda^3 \\ -a^*\lambda & 1 & c\lambda^2 \\ -b^*\lambda^3 & -c^*\lambda^2 & 1 \end{pmatrix}. \quad (7)$$

A precise matching of the CKM matrix including deviations from unity of diagonal elements, $|V_{ub}| \neq |V_{td}|$ and phase structure has to be performed at higher order in $f_\chi^{u_i,d_i}(\tilde{x}_i^{u,d}, \tilde{y}_i^{u,d})$.

3. Phenomenology of RS-A₄ and constraints on the KK scale

The main difference between the RS-A₄ setup and an anarchic RS flavor scheme [8] lies in the degeneracy of fermionic LH bulk mass parameters, which implies the universality of LH zero mode profiles and hence forbids gauge mediated FCNC processes at tree level, including the KK gluon exchange contribution to ϵ_K . The latter provides the most stringent constraint on flavor anarchic models, together with the neutron EDM [8, 10]. However, the choice of the common LH bulk mass parameter, c_q^L is strongly constrained by the matching of the top quark mass ($m_t(1.8\text{ TeV}) \approx 140\text{ TeV}$) and the perturbativity bound of the 5D top Yukawa coupling, y_t . Most importantly, when considering the tree level corrections to the $Zb\bar{b}$ coupling against the stringent EWPM at the Z pole, we realize [1] that for an IR scale, $\Lambda_{IR} \simeq 1.8\text{ TeV}$ and $m_h \approx 200\text{ GeV}$, c_q^L is constrained to be larger than 0.35. Assigning $c_q^L = 0.4$ and matching with m_t we obtain $y_t < 3$, which easily satisfies the 5D Yukawa perturbativity bound. The constraint on c_q^L from $Zb\bar{b}$ has a moderate dependence on the Higgs mass, such that the constraint $\Lambda_{IR} > 1.8\text{ TeV}$ for $c_q^L = 0.35$ and $m_h \approx 200\text{ GeV}$, is relaxed to $\Lambda_{IR} > 1.3\text{ TeV}$ for $m_h \approx 1\text{ TeV}$ [13].

4. Dipole Operators and FCNC processes

FCNC processes provide us with some of the most stringent constraints for physics beyond the SM and this is also the case for the framework of flavor anarchic models in warped extra dimensions [8, 9, 10]. In the quark sector, significant bounds on the KK mass scale typically arise from the neutron electric dipole moment (EDM), the CP violation parameters, $Re(\epsilon'/\epsilon_K)$

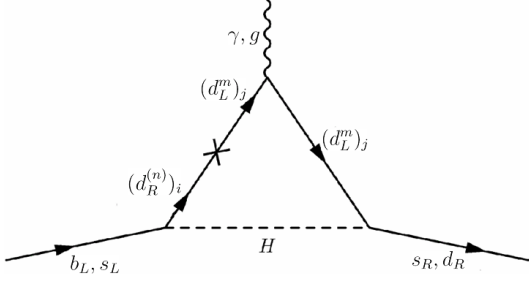


Figure 2. One-loop down-type (neutral Higgs) contribution to $b \rightarrow s\gamma$, ϵ'/ϵ_K and the neutron EDM (for external d quarks). The analogous one-loop up-type contribution (charged Higgs) contains internal up-type KK modes.

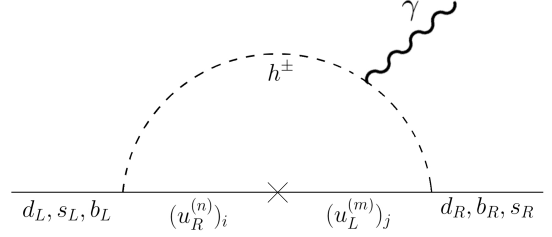


Figure 3. Charged Higgs one-loop contribution to $b \rightarrow s\gamma$ and the neutron EDM. The latter has external d quarks.

and ϵ_K , and radiative B decays such as $b \rightarrow s\gamma$. All these processes are mediated by effective dipole operators. It is also well known [19] that SM interactions only induce, to leading order, the single chirality operators $O_{7\gamma}$ and O_{8g} ($j > i$)

$$O_{7\gamma(8g)} = \bar{d}_L^i \sigma^{\mu\nu} d_R^j F_{\mu\nu} (G_{\mu\nu}). \quad (8)$$

The new RS- A_4 contributions to the FCNC processes we are interested in are generated at one-loop by the Yukawa interactions between SM fermions and their KK excitations, leading to the diagrams shown in Fig. 2 and Fig. 3.

In the mass insertion approximation, the flavor part of the corresponding amplitude can be written in terms of spurions [8]. To illustrate it, we focus on the down type contribution to the dipole operators in Fig.2, for which the corresponding Wilson coefficient is given by:

$$(C_{7\gamma(8g)}^{d-type})_{ij} = A^{1L} \frac{v}{M_{KK}} \left(F_Q \hat{Y}_d \hat{Y}_d^\dagger \hat{Y}_d F_d \right)_{ij}, \quad (9)$$

where \hat{Y}_d are the 5D Yukawa matrices and the fermion profile matrices are $F_{Q,u,d} = \text{diag}(f_{Q_i,u_j,d_j}^{-1}) = (1/\sqrt{2k}) \text{diag}(\hat{\chi}_{0Q_i,u_i,d_i})$ and $\hat{\chi}_{0Q_i,u_i,d_i}$ is the canonically normalized zero mode wave function evaluated on the IR brane. Finally, the factor $A^{1L} = 1/(64\pi^2 M_{KK})$ comes from the one-loop integral for the diagram in Fig. 2.

To account for overlap effects and illustrate the flavor patterns generated in RS- A_4 we write the LO mass matrix for the first generation in the down-type sector following [9, 10], including the zero modes and first level KK modes and overlap effects [13]

$$\frac{\hat{\mathbf{M}}_d^{KK}}{(M_{KK})} = \begin{pmatrix} \bar{Q}_L^{d(0)} \\ \bar{d}_L^{(1--)} \\ \bar{Q}_L^{d(1)} \\ \bar{d}_L^{(1+-)} \end{pmatrix}^T \begin{pmatrix} \check{y}_d f_Q^{-1} f_d^{-1} r_{00}x & 0 & \check{y}_d f_Q^{-1} r_{01}x & \check{y}_u f_Q^{-1} r_{101}x \\ 0 & \check{y}_d^* r_{22}x & 1 & 0 \\ \check{y}_d f_d^{-1} r_{10}x & 1 & \check{y}_d r_{11}x & \check{y}_u r_{111}x \\ 0 & \check{y}_u^* r_{222}x & 0 & 1 \end{pmatrix} \begin{pmatrix} d_R^{(0)} \\ Q_R^{d(1--)} \\ d_R^{(1)} \\ \tilde{d}_R^{(1+-)} \end{pmatrix}, \quad (10)$$

where we factorized a common KK mass scale M_{KK} , $\check{y}_{u,d} \equiv 2y_{u,d}v_\Phi^{4D}e^{k\pi R}/k$ and the perturbative expansion parameter is defined as $x \equiv v/M_{KK}$. In the above equation the various r 's denote the ratio of the bulk and IR localized effective couplings of the modes corresponding to the matrix element in question. For simplicity, we define $r_{111} \equiv r_{11-+}$, $r_{101} \equiv r_{01-+}$, $r_{22} \equiv r_{1-1-}$, $r_{222} \equiv r_{1-1+-}$ and the notation for the rest of the overlaps is straightforward. The corresponding

Yukawa matrix, \hat{Y}_{KK}^d is obtained by simply eliminating x and the 1's from the above matrix and it leads the flavor structure of the contributions of $(++)$ and $(-+)$ KK modes to the processes in Figs. 2 and 3, including overlap effects [13],

$$\begin{aligned} (C_{7\gamma(8g)}^{d,u})_{(++)} &\propto F_Q \hat{Y}_{d,u} r_{01}(c_{Q_i}, c_{d_{\ell_1}, u_{\ell_1}}, \beta) \hat{Y}_{d,u}^\dagger r_{11}(c_{d_{\ell_1}, u_{\ell_1}}, c_{Q_{\ell_2}}, \beta) \hat{Y}_{d,d} r_{10}(c_{Q_{\ell_2}}, c_{d_j, d_j}) F_d, \\ (C_{7\gamma(8g)}^{d,u})_{(-+)} &\propto F_Q \hat{Y}_{u,d} r_{01-+}(c_{Q_i}, c_{u_{\ell_1}, d_{\ell_1}}, \beta) \hat{Y}_{u,d}^\dagger r_{1-+1}(c_{u_{\ell_1}, d_{\ell_1}}, c_{Q_{\ell_2}}, \beta) \hat{Y}_{d,d} r_{10}(c_{Q_{\ell_2}}, c_{d_j, d_j}) F_d. \end{aligned} \quad (11)$$

Considering the degeneracy of LH bulk mass parameters in the RS-A₄ setup and using the ZMA diagonalization matrices to rotate the corresponding contribution to the mass basis we obtain for the down type contribution in Fig. 2 [13]:

$$\begin{aligned} (C_{7\gamma(8g)}^{d-type})_{ij} &= \frac{m_{d_i} A^{1L} f_Q^2}{v^2 M_{KK}} \left[V_R^{d\dagger} \text{diag}(f_{d,s,b}^2) (\hat{r}_{00}^d)^{-1} \tilde{r}_{01}^d \tilde{r}_{11}^d (\hat{r}_{00}^d)^{-1} V_R^d \text{diag}(m_{d,s,b}^2) \right. \\ &\quad \left. \times V_R^{d\dagger} (\hat{r}_{00}^d)^{-1} \hat{r}_{10}^d V_R^d \right]_{ij}, \end{aligned} \quad (12)$$

where $\tilde{r}_{01}^{u,d} \tilde{r}_{11}^{u,d} = \hat{r}_{01}^{u,d} \hat{r}_{11}^{u,d} + \hat{r}_{01-+}^{u,d} \hat{r}_{1-+1}^{u,d}$ and all overlap matrices are real and diagonal. Since the overlap correction factors turn out to have a very mild generational dependence [13], we can take them to be degenerate and parameterize their effect by an overall multiplicative factor, B_P^d .

To improve on the mass insertion approximation we diagonalize the one generation KK-zero mass matrix in Eq. (10) to directly obtain the physical coupling between a zero mode and the three KK modes of the same generation, including the previously unaccounted $(--)$ KK modes, while generational mixing effects are still estimated using the spurion structure of Eq. (12) with all overlap matrices set to $\mathbb{1}$ [9, 10, 13].

The down-type multiplicative overlap correction factor, B_P^d , corresponding to the process in Fig. 2, will thus be extracted from

$$(\mathcal{A}_{ij})_D^{\text{overlap}} = \frac{\sum_n ((O_L^{(d_i)KK})^\dagger \hat{Y}_{d_i}^{KK} O_R^{(d_i)KK})_{1n} ((O_L^{(d_i)KK})^\dagger \hat{Y}_{d_j}^{KK} O_R^{(d_i)KK})_{n1}}{(M_{KK}^{d_i(n)}/M_{KK})} \Bigg|_{\text{overlap}}. \quad (13)$$

We use the above procedure for obtaining the constraints on the KK scale arising from $\text{Re}(\epsilon'/\epsilon_K)$ and $b \rightarrow s\gamma$. However, by using the same procedure, the contribution to the neutron EDM turns out to be vanishing to first order in $f_\chi^{u,d_i}(\tilde{x}_i^{u,d}, \tilde{y}_i^{u,d})$. We can partially account for the latter by using the analog of Eq. (12) for the up type RS-A₄ neutron EDM contribution with non degenerate overlap correction factors. This yields an $\mathcal{O}(f_\chi^2 \Delta r)$ suppressed contribution, where Δr is the characteristic difference between nearly degenerate overlap correction factors and is numerically of $\mathcal{O}(0.01)$. The analytical estimations are then compared with the numerical solution of the full three generations case, where a diagonalization of the full 12×12 matrix is performed. The results of this comparison are reported in Fig. 4.

4.1. The custodial anarchic case

As a byproduct of our analysis we obtain the one generation KK estimations for a flavor anarchic setup with an additional $SU(2)_R$ doublet per generation and compare with the results of [9, 10]. The anarchic mass matrix is obtained from the matrix in Eq. (10) by eliminating all Yukawas and redefining $x = vY/M_{KK}$, where Y is the characteristic magnitude of the 5D anarchic Yukawa couplings. Generational mixing effects will simply contribute $f_{Q_i}^{-1} f_{d_j}^{-1}$ for the (ij) component of

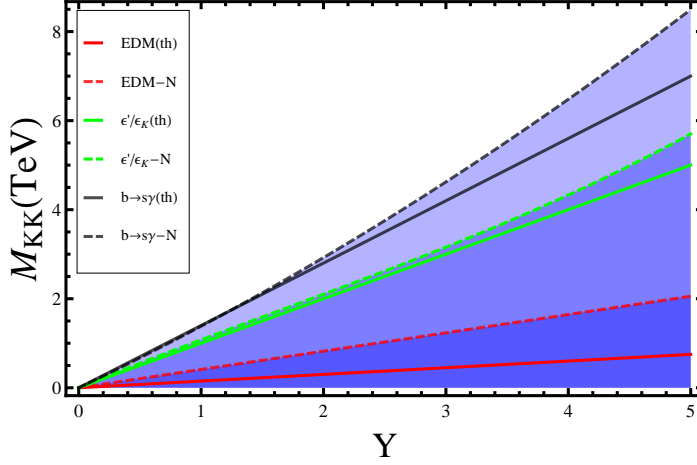


Figure 4. Bounds on the KK mass scale M_{KK} as a function of the overall Yukawa scale Y for the neutron EDM (bottom, red) ϵ'/ϵ (center, green) and $b \rightarrow s\gamma$ (top, black). The analytical (th) results (solid lines) are obtained within the one-generation approximation combined with the spurion-overlap analysis (with the exception of the EDM (see text)) and compared with the numerical (N) results (dashed lines) of the three-generation case. In both cases, predictions are obtained for the model parameters that lead to a realistic CKM matrix.

the dipole operators in Eq. (8). Together with the diagonalization of the mass matrix we obtain:

$$(C_{7\gamma(8g)}^d)_{ij}^{Cu.-An.} = \frac{f_{Q_i}^{-1} f_{d_j}^{-1} Y^3}{64\pi^2 M_{KK}^2} (r_{01}r_{10}(r_{11} + r_{111} + 9r_{22} + r_{222}) + r_{01}r_{101}(r_{11} + r_{111} + r_{22} + 9r_{222})) \quad (14)$$

Using the anarchic bulk mass assignments [8] and $\beta_H = 0$, which yields the weakest bounds as in [10], we obtain the constraints on the KK mass scale from $\text{Re}(\epsilon'/\epsilon_K)$ and $b \rightarrow s\gamma$ in the custodial anarchic case

$$(M_{KK})_{\epsilon'/\epsilon} \gtrsim 1.4 \text{ TeV} \quad (M_{KK})_{b \rightarrow s\gamma} \gtrsim 0.5 \text{ TeV} \quad (15)$$

When combined with the constraint from ϵ_K [10], which remains unchanged in the custodial anarchic case the resulting bound on the KK scale is:

$$(M_{KK})^{Cu.-An.} \gtrsim 6.6 \text{ TeV} \quad (16)$$

pushing the KK mass scale close to the limit of the LHC reach.

5. Conclusions

We have illustrated a model based on an A_4 flavor symmetry and implemented in a warped extra dimensional setup. The warped geometry supplements us, as usual, with solutions to both the gauge hierarchy problem and the fermion mass hierarchy. Simultaneously, the bulk A_4 flavor symmetry and its distinct SSB patterns towards the UV/IR branes by the A_4 flavons, Φ and χ , allows us to obtain a TBM neutrino mixing pattern and zero quark mixing as LO results, while NLO corrections induce realistic quark mixing and small deviations from TBM. While the experimentally allowed ranges for neutrino mixing angles [15] can also be explained with a bi-maximal mixing pattern at LO with large NLO corrections [21], they can be still accounted

for when considering NLO "cross-talk" and "cross-brane" interactions in the RS-A₄ model. In the quark sector, an exact matching of the CKM matrix is possible at the price of increased tuning of NLO 5D Yukawa couplings.

The most stringent constraint on the RS-A₄ model comes from the EWPM of the effective $Zb\bar{b}$ coupling. Together with the perturbativity bound of the 5D top Yukawa coupling it implies a constraint $M_{KK} \gtrsim 4 \text{ TeV}$ for $m_h \approx 200 \text{ GeV}$ and strongly constrains the common LH bulk mass parameter. On the other hand the constraints arising from the neutron EDM, ϵ'/ϵ_K and $b \rightarrow s\gamma$ were shown both analytically and numerically (see Fig. 4) to induce milder constraints, dominated by the one arising from $b \rightarrow s\gamma$.

To release the strong constraint from $Zb\bar{b}$ it is relevant to consider the implications of embedding RS-A₄ in a P_{LR} extended custodial setup [17, 22], where the dominant contributions to the anomalous Zbb coupling are strongly suppressed. However, since this embedding requires an extended non trivial fermion sector, we expect it to increase the bounds from the various FCNC processes we considered due to the presence of new KK modes and a richer flavor structure. In addition, we anticipate the typical prospects for observing $t \rightarrow cZ$ and $t \rightarrow ch$ and the reduction of Higgs production cross sections [22] to be mildly modified. A detailed study of the various phenomenological implications of a P_{LR} custodial RS-A₄ setup will be the subject of a future publication.

Acknowledgments

We thank the organizers of *DISCRETE'10 - Symposium on Prospects in the Physics of Discrete Symmetries* for the opportunity to present our work and for the lovely hospitality in Rome.

References

- [1] A. Kadosh and E. Pallante, JHEP **1008**, 115 (2010) [arXiv:1004.0321 [hep-ph]].
- [2] E. Ma and G. Rajasekaran, Phys. Rev. **D64**, 113012 (2001) K. S. Babu, E. Ma and J. W. F. Valle, Phys. Lett. **B552** 207 (2003); E. Ma, Phys. Rev. **D70**, 031901(2004) Talk at SI2004, Fuji-Yoshida, Japan, hep-ph/0409075.
- [3] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999) [arXiv:hep-ph/9905221]; L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 4690 (1999) [arXiv:hep-th/9906064].
- [4] C. Csaki, C. Delaunay, C. Grojean and Y. Grossman, JHEP **0810**, 055 (2008) [arXiv:0806.0356 [hep-ph]].
- [5] X. G. He, Y. Y. Keum and R. R. Volkas, JHEP **0604**, 039 (2006) [arXiv:hep-ph/0601001].
- [6] K. Agashe, A. Delgado, M. J. May and R. Sundrum, JHEP **0308**, 050 (2003) [arXiv:hep-ph/0308036].
- [7] M. Carena, E. Ponton, J. Santiago and C.E.M. Wagner, arXiv:hep-ph/0701055.
- [8] K. Agashe, G. Perez and A. Soni, Phys. Rev. D **71**, 016002 (2005) [arXiv:hep-ph/0408134];
- [9] K. Agashe, A. Azatov and L. Zhu, Phys. Rev. D **79**, 056006 (2009) [arXiv:0810.1016 [hep-ph]].
- [10] O. Gedalia, G. Isidori and G. Perez, Phys. Lett. **B 682**, 200 (2009) [arXiv:0905.3264 [hep-ph]].
- [11] K. Agashe, G. Perez and A. Soni, Phys. Rev. Lett. **93**, 201804 (2004) [arXiv:hep-ph/0406101];
- [12] G. Cacciapaglia, C. Csaki, J. Galloway, G. Marandella, J. Terning and A. Weiler, JHEP **0804**, 006 (2008)
- [13] A. Kadosh and E. Pallante, [arXiv:1101.5420 [hep-ph]].
- [14] P. F. Harrison, D. H. Perkins and W. G. Scott, Phys. Lett. B **458**, 79 (1999) [arXiv:hep-ph/9904297].
- [15] G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A. M. Rotunno, [arXiv:0809.2936 [hep-ph]]; T. Schwetz, M. A. Tortola, and J. W. F. Valle, New J. Phys. **10** (2008) 113011 [arXiv:0808.2016[hep-ph]].
- [16] C. Amsler *et al.* [Particle Data Group], Phys. Lett. **B667** 1 (2008).
- [17] K. Agashe, R. Contino, L. Da Rold and A. Pomarol, Phys. Lett. B **641**, 62 (2006) [arXiv:hep-ph/0605341].
- [18] W. D. Goldberger and M. B. Wise, Phys. Rev. Lett. **83**, 4922 (1999) [arXiv:hep-ph/9907447]; G. Cacciapaglia, C. Csaki, G. Marandella and J. Terning, JHEP **0702**, 036 (2007) [arXiv:hep-ph/0611358].
- [19] G. Buchalla, A. J. Buras and M. E. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996) [arXiv:hep-ph/9512380].
- [20] C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006) [arXiv:hep-ex/0602020].
- [21] L. Merlo, Talk given at DISCRETE10 - Symposium on Prospects in the Physics of Discrete Symmetries.
- [22] S. Casagrande, F. Goertz, U. Haisch, M. Neubert and T. Pfoh, JHEP **1009**, 014 (2010) [arXiv:1005.4315 [hep-ph]].